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# Deforestation, new migration pathways and outbreaks of the Red locust *Nomadacris septemfasciata* (Orthoptera: Acrididae) in the Sofia river basin (Madagascar)

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**RÉSUMÉ.** La superficie de la forêt malgache a considérablement diminué sous l'effet de la culture sur brûlis, pratique encore utilisée dans le nord-ouest du bassin de la Sofia. Dans cette zone, des pullulations récentes et sans précédent du criquet nomade *Nomadacris septemfasciata* (Serville, 1838) causant des ravages sur l'agriculture ont été observées de 2000 à 2003. Le criquet nomade a atteint la phase grégaire en formant des bandes larvaires et des essaims pour la première fois dans cette zone en 2002. La disparition de la forêt, entrave naturelle aux migrations du criquet, pourrait favoriser les migrations et permettrait le regroupement des populations acridiennes. Pour répondre à cette question, nous avons réalisé une étude diachronique par télédétection à partir de 2 images SPOT de 1986 et 2004 sur la région nord du bassin de la Sofia. L'évolution du couvert végétal met en évidence la déforestation et une fragmentation des forêts originelles. Comme l'attestent les données acridiennes, de nouvelles voies privilégiées de déplacement donnent accès à des sites de ponte auparavant inaccessibles et permettent aux criquets de se multiplier et se regrouper.

**ABSTRACT.** The surface area of the Malagasy forest has been considerably decreased by slashing and burning, a practice still used in the northwest (Sofia basin). In this area, unprecedented outbreaks of the red locust *Nomadacris septemfasciata* (Serville, 1838) caused crop damage (rice, maize and many leguminous plants) from 2000 to 2003. The red locust reached the gregarious phase for the first time in this area in 2002. Recent alterations of environmental conditions may have led to this unprecedented outbreak. Would fragmentation and disappearance of forest, which is an obstacle to locust migration, increase migration and the crowding of locust populations by migration? To answer this question, remote sensing was used to detect the change of land cover between 1986 and 2004 with 2 SPOT images centred on the northeast of the Sofia watershed. The evolution of land cover shows large deforestation and landscape fragmentation. Locust field data confirm that new preferred migration pathways give access to formerly inaccessible areas that are favourable for red locust reproduction.

**MOTS CLÉS :** Madagascar, locuste, migration, déforestation, télédétection

**KEY WORDS:** Madagascar, locust, migration, deforestation, remote sensing

## 1. Introduction

The slash and burn practice is responsible for a decrease of the surface area of the Malagasy forest and also deeply modifying the structure of the vegetation cover (Green & Sussman, 1990). The frequent use of fire is replacing native species with exotic, aggressive species and favours grasses over woody species, creating treeless landscapes that are of minimal productive and ecological value (Styger *et al.*, 2007). Today, deforestation continues even though the total forest remnants are among the most critical of 25 biodiversity hotspots (Myers *et al.*, 2000).

The practice of fire is also used in the Sofia catchments (northwest part of the island), which were originally covered with high and dense sclerophyllous forest (Koechlin *et al.*, 1974). A diachronic study (change in a phenomenon over a period of time) of the vegetation cover from 1954 to 1995 in the nature reserve of Manongarivo in the north of Sofia revealed that the speed of deforestation has clearly accelerated since 1987 (Gautier *et al.*, 1999). But up to now, no study in the Sofia area evaluated the importance of deforestation and the side effects of the openness of the landscape on outbreeding animal species.

In parallel to these environmental changes, the red locust *Nomadacris septemfasciata* (Serville, 1838) underwent an exceptional proliferation in the Sofia area between 1999 and 2003. Gregarious red locusts (larval bands and swarms) were observed and described for the first time in 2002 (Franc *et al.*, 2005). Prior to this period, this locust was responsible for only local outbreaks on the western side of the island. Before 1999, populations were not crowded enough to cause an invasion over several years at a large scale. Various studies revealed the bioecology of the red locust (Frappa 1936, Têtefort & Wintrebert 1967, Randrianasolo, 1978, Franc *et al.* 2005). It lives in open areas and has only one generation per year with two distinct periods of development: reproduction and larval development in the rainy season then adult diapause in the dry season. It carries out migrations over long distances in solitary (isolated) or gregarious (crowded in swarms) phases.

How did such outbreaks appear and how did the red locust succeed in its transformation to the gregarious phase in the Sofia area? Are these changes related to intense deforestation?

To gregarize, a locust needs to multiply and gather. However, in northwestern Madagascar, the insect carries out the two major parts of its cycle in distinct areas (fig. 1): larval development in the entire Sofia area and imaginal diapause in the eastern relief located on the toe of the Malagasy highlands (Franc & Duranton, 2007). The insect undertakes two seasonal migrations to pass from one area to the other: migration from the east towards the west in November to join the reproduction areas, then migration from the west towards the east in April to join the diapause areas.

The red locust in solitary phase flies at low altitude in the twilight if the temperature is higher than 22°C (Chapman, 1959). It generally flies according to the prevailing winds. To limit losses in population, like other locusts, the red locust does not fly randomly, but follows preferred migration pathways of three types (Duranton *et al.*, 1979): 1) orography, 2) hydrography, and 3) discontinuity of vegetation cover. The orographical pattern follows cliffs or edges of mountains, i.e. the insect will not pass over steep slopes. The hydrographic pathways are formed by river valleys. Lastly, without other directional elements, the red locust preferentially follows the axes of cleared vegetation (Duranton *et al.*, 1979). Indeed, the insect has a visual optomotor response based on ground cover: it has a tendency to follow the limit of the white bands in grassy areas compared with the dark bands of forest areas (Preiss & Spork, 1995). Thus, the red locust will not colonize the vast dark areas covered with forest, but preferably remains in the open areas that appear light at twilight (Chapman, 1959).

The recent modifications of behaviour of the red locust (outbreak, gregarization) could be explained by the modification of its preferred migration pathways through deforestation in Madagascar. Deforestation could modify the preferred migration pathways of the red locust by opening new pathways related to the structure of the vegetation cover, as shown for others locusts (Despland, 2003; Jordan *et al.*, 2003). Connections between the eastern and western areas of the Sofia catchments could be multiplying, thus increasing the probability of colonization of favourable areas for laying at the beginning of the rainy season or for diapause at the beginning of the dry season.

In order to map and follow the phenomenon of deforestation, satellite data have been used for a long time (Green & Susman, 1990). Optical images were also used to assess the risk of locusts (Ji *et al.*, 2004; Silvanpillai *et al.*, 2007). Insofar as the migration pathways of the red locust are determined by topography and vegetation cover, remote sensing seems an appropriate tool for modelling.

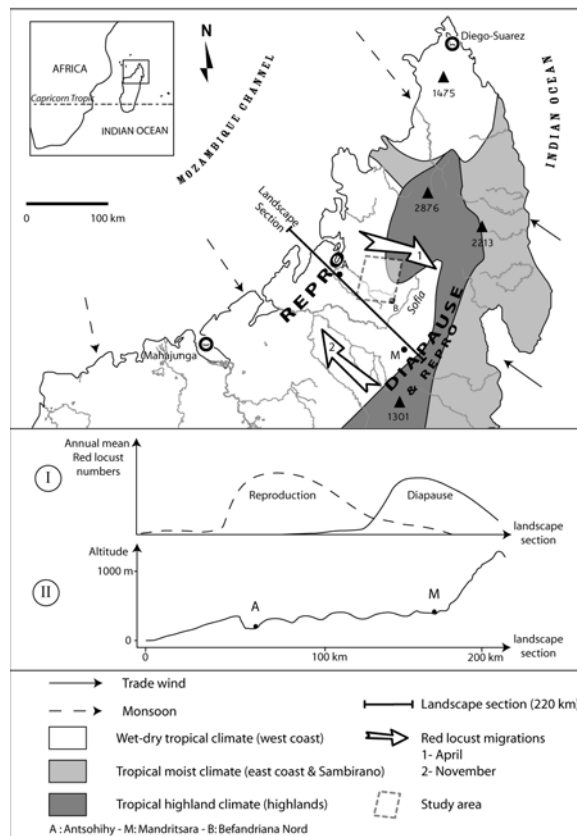
Our study thus seeks to characterize and quantify the evolution of vegetation cover since the 1980s using high resolution remote sensing data in a pilot area of the Sofia catchments concerned with the seasonal migrations of the red locust. Finally, we want to map and compare the old and currently preferred migration pathways.

## 2. Methods

### 2.1. Study area

The study area (2 600 km<sup>2</sup> in northwestern Madagascar) is in the northern portion of the Sofia catchments (fig. 1). It is bordered by two distinct areas: 1) the low altitude western part containing sedimentary soils where red locusts breed in the rainy season, and 2) the more elevated eastern part which lies on a crystalline platform, where the locusts retreat in the dry season for diapause.

There is a climatic gradient between the 2 areas. In the low altitude west (Antsohihy area), the tropical climate is contrasted with a hot and rainy season then a cool and very dry season. In the east, the climate is also tropical but attenuated with less rainfall but more atmospheric dampness in the dry season (Donque, 1975).



**Figure 1.** Study area in the north of Madagascar at the edge of the two main areas of the red locust (diapause and reproduction). Graph I shows the annual repartition of the red locust (field data collected between 2003 and 2006). Graph II shows the difference in altitude between these 2 complementary areas.

A part of the Bora Forest Reserve is situated in the western part of the study area. Theoretically, human activity has been prohibited there since 1964. However, there is a lack of monitoring and the neighbouring populations have practiced slash and burn – called *tavy* in Malagasy – for many years (Nicoll & Langrand, 1989). Crops grow at the expense of original forest formation. This original plant community corresponds to a tropical dry broadleaf dense forest (Humbert & Cours-Darne, 1965). The strata are composed of a dense and continuous tree layer of 25 meters in height, dominated by a discontinuous higher tree layer which can reach 40 m. The shrubby undergrowth is rather clear. The herbaceous layer is non-existent. Outside

of the forests, savannas are characterized by grasslands dominated by *Hyparrhenia rufa* (Nees) Stapf. and *Heteropogon contortus* (L.) P. Beauv. and a discontinuous woody layer with *Sclerocaria caffra* Sond. & *Bismarckia nobilis* Hildebrandt & H. Wendl. (Koechlin *et al.*, 1974).

The intermediate mixed formations, named *Savoka* in Malagasy, are the result of degradation due to the practice of *tavy* (Styger *et al.*, 2007). After 2 to 4 years of crops, if canopy closure is not disturbed by fires, the *Savoka* becomes dense: the woody cover is continuous and reaches 5 to 10 meters high. If the *Savoka* burns just after the slash and burn crops, the *Savoka* remains very open: an herbaceous cover dominates and cohabits with dense bushes, stumps, and shoots.

The crops areas are of 3 types. Hollows easily flooded are converted into irrigated rice. The slopes and edge of hollows are cultivated with dry crops (corn, manioc, leguminous plants) and arboriculture (banana plantations). Finally, forests are included in the *tavy* cycle for the culture of rainfed rice.

To map the migration pathways of the red locust, we used 4 classes of plant community. They are characterized by their canopy closure and offer various levels of migratory resistance to the red locust: the forest (dry forest and gallery forest), mixed (different types of *Savoka*), grasslands (savannas, meadows, and crops), and non-attractive areas (villages, water, and bare soil).

## 2.2. Remote Sensing Data

The selected satellite images needed to cover a maximum period to make the diachronic study as broad as possible. To discriminate plant community, the period of optimal acquisition was at the end of the rainy season (from April to July) which exhibits the maximum contrast between the wet and dry lands. In addition, it was necessary to avoid images that contained cloud cover and exhibited suboptimal angles of incidence. The images of July 1986 and April 2004 were 2 SPOT images available for this area fitting the constraints and they allowed a comparison of vegetation over a long period (18 years). The common surface of these satellite images cover 2 600 km<sup>2</sup>. The design features of these images are reported in table 1.

**Table 1:** Characteristics of the two satellites images used for the diachronic study of the red locust migration pathways

Date	Hour	Satellite	Instrument	Spectral mode	Viewing-angle	
					Orientation	Incidence
20/07/1986	07:05	SPOT1	HRV 1	XS	9,1	R2,2
26/04/2004	07:20	SPOT4	HRVIR 1	XI	8,1	L26,6

HRV: High Resolution in Visible. HRVIR: High Resolution in Visible and Infrared. XS: Multi Spectral mode (4 bands). XI: Multi spectral mode (3 bands). R: Right (positive angle). L: Left (negative angle)

To delimit orography and slopes, we used a 90 meters resolution digital elevation model (DEM) acquired by the Shuttle Radar Topography Mission of NASA in 2002 and downloaded free from the Web site: <http://glcf.umiacs.umd.edu>.

The analysis of these images followed several stages: digital processing, mapping of migration pathways, and the study of their evolution.

### **2.3. Digital processing**

#### *Geometrical correction and sampling*

The images were georeferenced with ground points collected with a Global Positioning System (GPS) using Garmin receiver. The results of the registration are satisfactory for the 2 images (roots mean square RMS error < 1 m.). Nevertheless, we noted a slight shift (80m) in the eastern relief of the study area.

#### *Remote sensing methodology for change detection*

A post-classification comparison method was selected. Indeed, this method appears the best adapted, taking into account the average quality of registration in the eastern relief. This method required careful consideration for each image, as the quality of comparison is directly dependent upon classifications (Mas, 2000).

For each date, a map of the plant communities was obtained by classification using the ERDAS software. For each of the 4 plant communities, a series of training sites (samples of pixels) were selected in the image by photo-interpretation. The selection of training sites was made distinctly for each image, i.e. 456 for 2004 and 412 for 1986. The algorithm used for each supervised classification is the maximum likelihood. This algorithm establishes a probability of membership for a pixel to each class and assigns this pixel to the closest class (Jensen, 2005).

#### *Choice of spectral bands*

From the original images composed of 4 bands (Green, Red, Near InfraRed, & Middle InfraRed), we produced nonspectral images to discriminate the various types of vegetation. We initially produced an image in PCA (Principal Components Analysis) and chose the bands richest in information. Then, we calculated the Normalized Difference Vegetation Index (NDVI) to reduce the effects of illumination and shade which can be created by the relief (Jensen, 2005). These two nonspectral images were added to the original SPOT bands (table 2).

**Table 2:** Bands of the 2 false colour composite Spot image used for the classification of plant communities

False colour composite image		
Band	1986	2004
1	XS1*	XS1*
2	XS2*	XS2*
3	XS3*	XS3*
4	PCA1	XS4
5	PCA2	PCA1
6	PCA3	PCA2*
7	NDVI*	PCA3
8		PCA4
9		NDVI

XS: original SPOT bands. PCA: Bands resulting from Principal Component Analysis. NDVI: Normalized Difference Vegetation Index. \* Bands used for the classification

The Euclidean distance method was used to determine the bands with the maximum separability for each classification (indicated by \* in table 2).

The cloudy areas and their shade, present only in the 1986 image, were classified independently then transformed into a mask. The shades of relief, with biased spectral information, were isolated from the image and classified separately by taking specific training sites.

#### *Accuracy assessment*

The accuracy of the classifications was evaluated using an error matrix and the Kappa coefficient. To do this, we used reference points (114 for 1986 and 103 for 2004) selected by photo-interpretation.

#### **2.4. Mapping migration pathways and their evolution**

Determining the best route through an area is one of the oldest spatial problems (Kenchoo & Wandjae, 2000). The use of the “Least Cost Path” procedure for identifying an optimal route based on user-defined criteria has been used extensively in GIS applications for setting linear features and corridors. Whether the application involves the movement of herds of shoppers, or locating highways, or electric transmission lines, the procedure is fundamentally the same: 1) develop a discrete cost surface that indicates the relative preference for routing at every location of the study area, 2) generate an accumulated cost surface characterizing the optimal connectivity from a starting location (source) to all other locations based on the intervening relative preferences, and 3) identify the path of least resistance to a desired end location (sink) along the accumulated surface (Hargrove *et al.*, 2004).

We used this Least Cost Path method to connect eastern points (the sources, the departure point corresponding to the diapause area) to western points (the sink, the destination corresponding to the reproduction area). The sources were selected in the valleys of the mountains where the locusts are located during the diapause period (Franc & Duranton, 2007). Six sinks were chosen in the west with distances of ten kilometres from each other.

For each plant community, a displacement cost was fixed (table 3). We fixed a high displacement cost for the forest which plays a barrier role in the displacement of the locust. In contrast, the grassy and non-attractive areas are open areas with a low displacement cost. The mixed formations have an intermediate cost. Orography was taken into account through the slopes; a very high displacement cost was fixed to slopes of more than 30°, making it impossible to cross such a relief.

**Table 3:** *Migration cost for the red locust for each plant community*

<b>Plant Community</b>	<b>Migration cost</b>
Forest (dry forest, gallery forest)	20
Mixed ( <i>Savoka</i> , fallow)	5
Grassy (savannas, meadows, steppes, crops)	1
Non Attractive (villages, bare soil, water)	1
Slope > 30°	1000

A matrix of the displacement costs was generated for each image. The function "Cost/Distance" by ArcGIS was used to isolate the directed migration pathways from east to west. For each image, a calculation of cost (cost path) to join the sources and the sinks was carried out. The values of cost were brought back to the length of each corridor. They can be interpreted as a probability of being used by the locust. Schematically, 3 classes of probability were chosen: low, medium, and high. These corridors were used to map the old and actual preferred migration pathways for the red locust.

### **2.5. Validation of the migration pathways**

We used locust field data to validate the highlighted migration pathways. If a migration pathway is indeed functional, the winged red locust will use it and lay along this way and further away in the western portion of the study area. We thus projected the last hopper bands over the period of 2000 to 2003. On the whole, 227 hopper bands were collected by the Malagasy National Locust Centre.

## **3. Results**

Two maps of plant community resulted from the classifications of 1986 and 2004 (fig. 2). Table 4 present the total precision of each classification. The corresponding error matrices gave overall satisfactory results: a total precision of



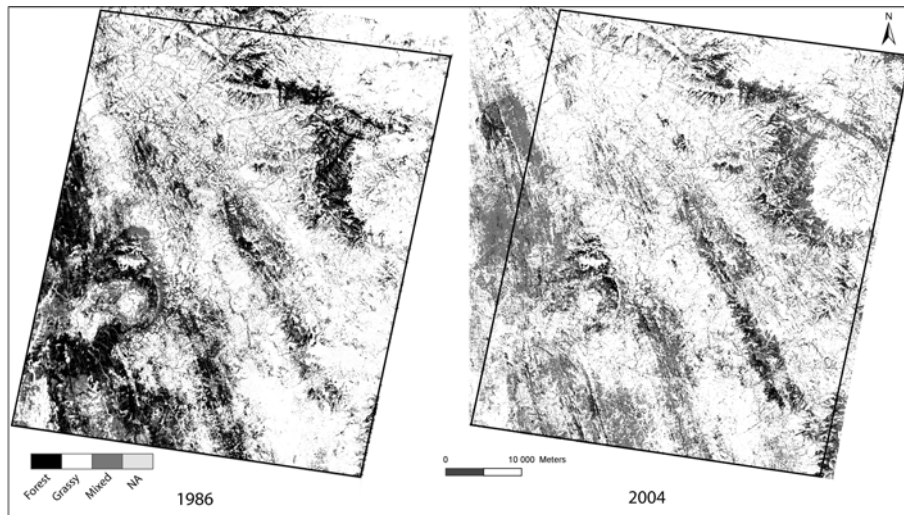
93% in 1986 and 88% in 2004. The main errors come from the mixed class. This class includes some patches of forest in 1986, and some patches of grasslands. These inevitable errors are due to the varied composition of mixed habitats.

**Table 4:** Error matrix for 1986 map

	Classes	Kappa	Reference				Total	Commission error	Omission error
			Forest	Mixed	Grassy	NA			
1986	Forest	0.959	37	1	0	0	38	90.2%	97.4%
	Mixed	0.769	4	17	0	0	21	85.0%	80.9%
	Grassy	0.899	0	2	50	1	53	100.0%	94.3%
	NA	1.000	0	0	0	2	2	66.7%	100.0%
	Total	0.891	41	20	50	3	114		
2004	Forest	0.652	4	0	2	0	6	100.0%	66.7%
	Mixed	0.745	0	7	2	0	9	53.9%	77.8%
	Grassy	0.584	0	6	73	2	81	94.8%	90.1%
	NA	1.000	0	0	0	5	5	71.4%	100.0%
	Total	0.680	4	13	77	7	101		

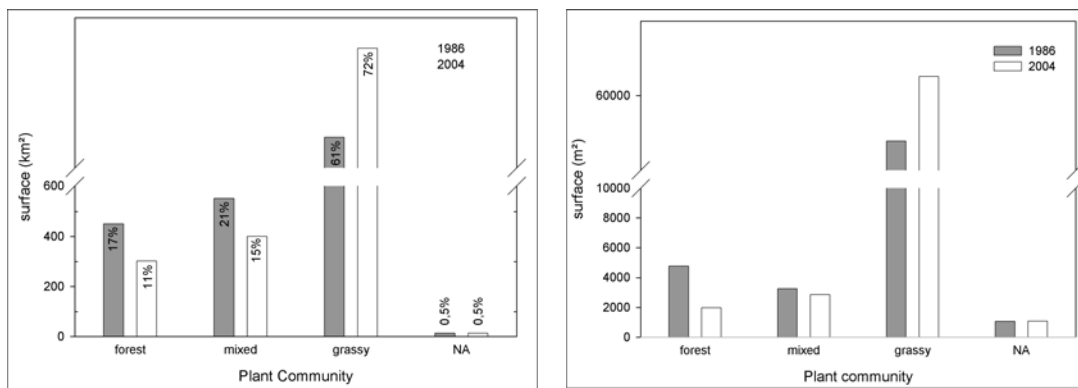
Global Accuracy: 1986: 92.98%. 2004: 88.12%. NA: Non Attractive areas

### 3.1. Plant Communities



**Figure 2.** Plant communities in 1986 and 2004 mapped from a classification of a Spot satellite image. Projection UTM, Datum WGS 1984. (NA: Non attractive areas)

The comparison of the 2 maps shows a reduction of forest and an increase in grassy formations (fig. 3). Between 1986 and 2004, deforestation was evident on 2 levels: 1) vast forest patches disappeared completely (fig. 3), the phenomenon of landscape fragmentation (reduction in the size of the patches). 2) In a logical parallel, the structure of forest formations changed; the surface of mixed formations also decrease but the mean surface of patches stay the same. Above all, surface of the grassy formations extended, which confirms the consecutive process of deforestation to clearing (savanization).



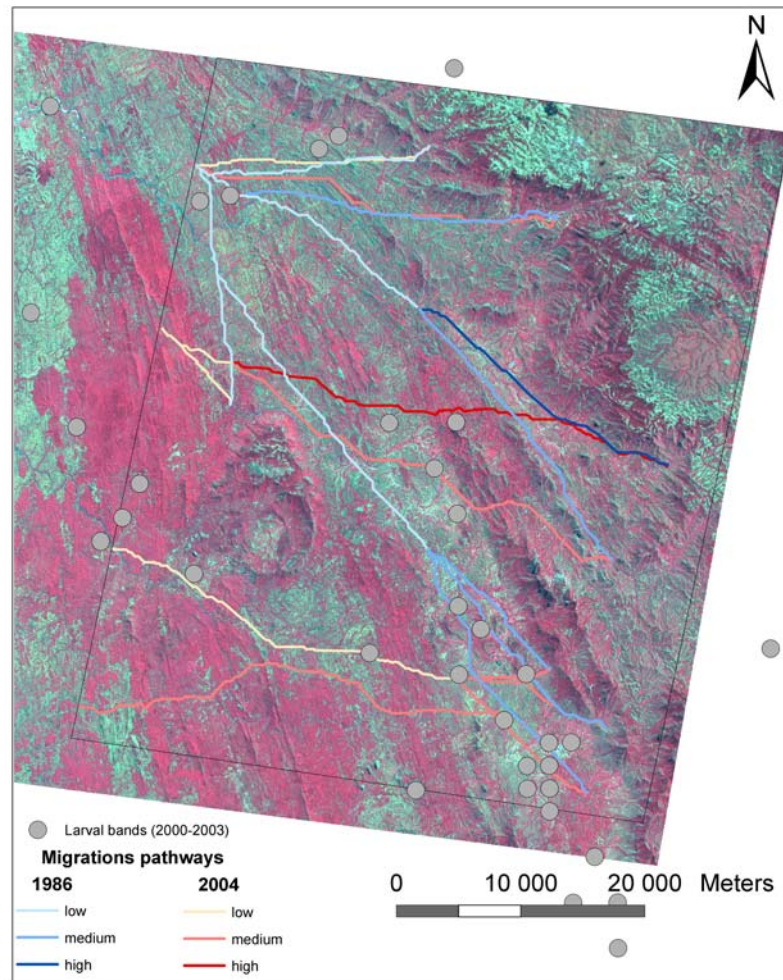
**Figure 3.** Evolution of the plant communities' surfaces (km<sup>2</sup>) and of the mean surfaces of patch of each plant community between 1986 and 2004 delimited from the Spot image. (NA: Non attractive areas)

There was no mixed area in 1986 that recovered and became forest in 2004. All patches of forest in 2004 were forest in 1986. Only in rare cases did grassy zones change to mixed formations over this period, which attests to slight and local recovery of vegetation. In general, however, the forest area has been cleared over the 18-year period.

The Bora Forest Reserve became extremely fragmented. This is also evident in the south-eastern part of the image and the eastern slopes where forests dominated in 1986 but are cleared today.

### 3.2 Evolution of the migration of the red locust

In 1986, only the large grassy areas located in the northwest were accessible to the insect (fig. 4). The forests prevented any access to the west and southwest. By 2004, new pathways had been opened through these forests and the southwest areas became accessible.



**Figure 4.** Old and actual migrations pathways of the red locust mapped using Least cost path analysis. Hopper bands of the red locust during the plague period (2000-2003) projected on the false colour image (Spot 2004).

The hopper bands between 2000 and 2003 are located in these corridors. This shows their importance for the migration of the winged locusts that research laying areas at the beginning of the rainy season. The outbreaks far in the west are also in the continuation of these corridors. The 227 hopper bands observed between 2000 and 2003 took place, for the most part, along the migratory pathways. We can divide them into 3 distinct zones.

1) 71 hopper bands occurred in the southeast of the image: these landscapes are open and close to the diapause areas. They are thus easily colonisable by the winged locust.

2) 17 were on the pre-existing migration pathways of 1986 (the northwest of the zone) and 24 were in the direct continuation of these pathways.

3) 19 hopper bands were located along the two new migration pathways in the south of the image and 96 were on the direct continuation.

Half of the hopper bands can thus be explained by the creation of new migration pathways. These new pathways gave the locust direct access to new reproduction areas.

#### 4. Discussion

The diachronic study carried out with the SPOT satellite images allowed us to define the old and new migration pathways. The post-classification comparison method tolerates the use of images rather distant from a radiometric point of view. On the other hand, excellent field knowledge was required for choosing the training and validation sites.

In 1986, 4 main pathways existed. All were directed towards the northwest of the study area. In 2004, the old pathways were still usable, but 3 new pathways appeared in the southwest of the study area. The large Bora forest, impenetrable to the red locust in 1986, was sufficiently cleared to open new migration pathways. The forest forms a screen for the locust. It prevented or delayed the colonization of habitats, even favourable ones, situated in its continuation (Duranton *et al.*, 1979). The opening of new migration pathways in the southwest cancels this property of the forest. The old pathways all lead to the reproduction areas in the north of Antsohihy. On the other hand, the southern reproduction areas (the valleys of Tsinjomorona and Doroa) were inaccessible in 1986. However, hopper bands occurred there between 2000 and 2003 (fig. 4, see also Franc *et al.* 2007). The two migration pathways that opened in the south of the study area gave access to new laying areas.

The probability for an insect to find suitable climatic conditions for reproduction is better as the colonisable areas are widened. This increases the spatial area of the potential laying zones. This allows the insect to lay under varied climatic conditions, thus producing much higher numbers during favourable climatic years. This also allows for the maintenance of high numbers during unfavourable years. However, to

gregarize, it is necessary that the locust multiplies its numbers and maintains them high over several consecutive years. The opening of these new migration pathways is thus one of the explanatory factors for the recent gregarisation of the red locust which occurred in Sofia between 2000 and 2003.

Our study area is a summary of the Sofia catchments, connecting the elevated areas favourable for diapause to low areas favourable for the laying period. But the red locust moves over long distances and the Sofia catchments cover more than 50 000 km<sup>2</sup>. A work on a smaller scale using medium resolution data could trace the migration pathways on a greater surface.

The centre of the Sofia catchments was also covered with forest in the year 1970 (Koechlin *et al.*, 1974). Our field and aerial surveys carried out on from Mandritsara to the mouth of Sofia revealed the same signs of deforestation. It is highly probable that new migration pathways also opened in these areas. At the scale of the Sofia catchments, the locust currently has many more possibilities for migration with straight itinerary due to deforestation.

Elsewhere in Madagascar, a study in the south highlighted displacements from east to west (Lecoq *et al.*, 2006). Investigations in the west central area also showed seasonal complementarities between diapause areas in the east and western laying areas (Franc *et al.*, 2007). But in these two cases, no new migration pathway seems to have been created by deforestation.

Up to now, no outbreak area, as defined by Uvarov (1977), had been clearly identified and delimited in Madagascar for the red locust. The Sofia catchments could constitute such an outbreak area. Indeed, it is composed of ecologically complementary areas colonized for the 2 periods of the locust cycle. Moreover, we show here that these 2 areas are now in communication by migration pathways.

Migratory connectivity between various areas is essential to understanding the outbreaks of the migrant species (Webster *et al.*, 2002; Cheke & Tratalos, 2007). A landscape genetic study would be useful for the spatial detection and location of genetic discontinuities between populations (Guillot *et al.*, 2005; Holzhauer *et al.*, 2006). The description of the relationship between the adult diapause metapopulations in the east of the Sofia catchments with the larval populations dispersed in the west would allow the determination of the sources and sink patches of populations highlighted by the migration pathways traced here by remote sensing.

Deforestation has direct visible consequences on biodiversity and soil erosion (Styger *et al.*, 2007). The health of forests was studied in relation to deforestation (Holdenrieder *et al.*, 2004) because tree pathogens propagate according to heterogeneous spatial patterns of flow and isolation. Landscape pathology is a field that is now emerging from the transdisciplinary cooperation between forest pathologists and landscape ecologists. The emergence of new crop pests, such as locusts, in relation to deforestation is still a field to be explored.

## **5. Conclusion**

The analysis of high resolution, remotely sensed images joined to a geographical information system led to the first map of the migration pathways of the red locust in Madagascar. The combination of these data with slope information and the hydrographic network within a GIS made it possible to analyze the spatial and temporal evolution of landscapes and their impact on the potential of locust displacement.

The slash and burn practice modified the vegetation cover between 1986 and 2004 through the decline of forests and increases of grassy areas. Forest fragmentation created new migration pathways for the red locust. The locust can now reach suitable laying areas in the southwest of our study area. The hopper bands from 2000 to 2003 located along these pathways attest to their effective use by the red locust.

In practical terms, this work shows that is possible to draw the migration pathway of this locust. The migration pathways can be used as field survey itinerary to estimate the level of population before the migration of the rainy season, and so deduce the level of future infestations and the logistic means to control them.

The deforestation and fragmentation of the landscape could also open new areas for laying for the red locust. These alterations contribute to create a new outbreak area for the red locust in the Sofia catchments.

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